

BNL 66455
April 19, 1999

HANDBOOK OF ACCELERATOR PHYSICS AND ENGINEERING

Editors: M. Tigner, Cornell
A. Chao, SLAC

Publisher: World Scientific

Sections written by Thomas Roser, BNL:

- 2.7.1 - Thomas - BMT equation
- 2.2.2 - Spin or Algebra
- 2.7.3 - Spin Rotators and Siberian Snakes
- 2.7.4 - Ring with Spin Rotator and Siberian Snakes
- 2.7.5 - Depolarizing Resonances and Spin Flippers
&
- 7.6.2 - Proton Beam Polarimeters

BNL-66455

introducing a large number of background beam-ion events. No indirect beam-beam compensation scheme has moved beyond the conceptual stage, to date.

Betatron phase cancelation A single set of beam-beam resonances may be eliminated by adjusting the phase advance between neighboring IPs in a storage ring [18]. For example, if the phase advance between two IPs is $\Delta\phi_x = \Delta\phi_y = 2\pi(p/N + q)$ (p, q, N integers, p odd), then all beam-beam resonances of order N are canceled. This scheme, which has not been tried in practice, relies on the collision points being clustered - not smoothly distributed around the circumference. Other resonances, tune shifts, and tune spreads are left uncompensated.

References

- [1] Y.K. Batygin, T. Katayama, RIKEN-AF-AC-3, 1997
- [2] J.E. Augustin et al, p.113, Vol. 2, Proc. 7th Int. Conf. H. E. Acc. (1969)
- [3] G. Arzelia et al, p.150, Proc. 8th Int. Conf. H. E. Acc. (1971)
- [4] H. Zyngier, AIP Proc. 57 (1979) p.136
- [5] Ya.S. Derbenev, 3rd All Union Conf. on Acc. (1972); INP 70-72 (1972); SLAC TRANS 151 (1973)
- [6] E. Keil, Proc. 3rd ICFA Beam Dyn. Wkshp. (1989); CERN-LEP-TH/89-37 (1989)
- [7] Orsay SR Group, IEEE Trans. Nucl. Sci. NS-26, No.3 (1979) 3559
- [8] R. Chehab et al, Proc. 11th Int. Conf. High Energy Acc. (1980)
- [9] V.E. Balakin, N.A. Solyak, Proc 13th Int. Conf. High Energy Acc. (1986)
- [10] N. Solyak, INP 88-44, Novosibirsk (1988)
- [11] D. Whittum, R. Siemann, PAC 97
- [12] Y. Chin, DESY 87-011 (1987)
- [13] J.B. Rosenzweig et al, Proc. Lake Arrowhead Wkshp., AIP Press (1989) p.324
- [14] R. Talman, unpublished (1976)
- [15] E. Tsyganov et al, SSCL-519, (1993); JINR-E9-96-4, Dubna (1996)
- [16] V. Shiltsev, D. Finley, FERMILAB-TM-2008 (1997)
- [17] D. Whittum et al, LBL-25759 (1988)
- [18] S. Peggs, Proc. Wkshp. on AP Issues for SSC, UM HE 84-1 (1984) p.58

2.7 POLARIZATION

2.7.1 Thomas-BMT equation

T. Roser, BNL

Precession of polarization vector \vec{P} of a particle with mass m and charge Ze [1, 2, 3, 4],

$$\begin{aligned} \frac{d\vec{P}}{dt} &= \vec{\Omega}_0 \times \vec{P} \\ \vec{\Omega}_0 &= -\frac{Ze}{m\gamma} \left[(1 + G\gamma) \vec{B}_\perp + (1 + G) \vec{B}_\parallel \right. \\ &\quad \left. + \left(G\gamma + \frac{\gamma}{\gamma + 1} \right) \frac{\vec{E} \times \vec{v}}{c^2} \right] \end{aligned} \quad (1)$$

\vec{P} is defined in the particle rest frame, \vec{E} and \vec{B} in the laboratory frame. $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel$, $\vec{B}_\parallel = (\vec{v} \cdot \vec{B})\vec{v}/v^2$.

In the frame rotating with \vec{v} given by the Lorentz force equation and assume $\vec{E}_\parallel = 0$,

$$\begin{aligned} \frac{d\vec{v}}{dt} &= \vec{\Omega}_c \times \vec{v} \\ \vec{\Omega}_c &= -\frac{Ze}{m\gamma} \left(\vec{B}_\perp + \frac{\gamma^2}{\gamma^2 - 1} \frac{\vec{E} \times \vec{v}}{c^2} \right) \\ \frac{d\vec{P}}{dt} &= \vec{\Omega} \times \vec{P} \\ \vec{\Omega} &= -\frac{Ze}{m\gamma} \left[G\gamma \vec{B}_\perp + (1 + G) \vec{B}_\parallel \right. \\ &\quad \left. + \left(G\gamma - \frac{\gamma}{\gamma^2 - 1} \right) \frac{\vec{E} \times \vec{v}}{c^2} \right] \end{aligned} \quad (2)$$

$G = \frac{g-2}{2}$ is the anomalous magnetic moment; $g = \frac{2m\mu}{Ze\hbar}$ is the gyromagnetic ratio (Landau factor).

	G	$\left \frac{mc^2}{G} \right $ [GeV]	$\left \frac{ZeG}{mc} \right $ $\left[\frac{\text{rad}}{\text{Tm}} \right]$
e	0.00115965	0.440649	0.680342
μ	0.00116592	90.6220	0.00330816
p	1.79285	0.523341	0.572843
d	-0.142562	13.1522	0.0227940
^3He	-4.19144	0.669910	0.895023
^3H	7.93689	0.353779	0.847401

Note:

(i) In rest frame:

$$\vec{\Omega}_0 = -\frac{e\hbar}{2m} \vec{B} = -\frac{e}{2m} (1 + G) \vec{B}.$$

(ii) For $\vec{B}_\parallel = 0$ and $\vec{E}_\perp = 0$ or $\gamma \gg 1$: $\Omega/\Omega_c = G\gamma$. This is the *spin tune* in this special case.

(iii) "Magic" Energy for which $\vec{\Omega}$ is independent of \vec{E} : $\gamma = \sqrt{1 + \frac{1}{G}}$.

References

- [1] B.W. Montague, Phys. Rep. 113 (1984) 1
- [2] L.H. Thomas, Phil. Mag. 3 (1927) 1
- [3] V. Bargmann, L. Michel, V.L. Telegdi, PRL 2 (1959) 435
- [4] S.Y. Lee, World Scientific (1996)

2.7.2 Spinor Algebra

T. Roser, BNL

Coordinate frame symbols and indices: (1,2,3)
 =(radial outward, longitudinal forward, vertical
 up) = ($\hat{x}, \hat{s}, \hat{y}$). Pauli matrices:

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$= \left[\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \right]$$

$$\sigma_1 \sigma_1 = \sigma_2 \sigma_2 = \sigma_3 \sigma_3 = I \quad (1)$$

$$\sigma_3 \sigma_1 = -\sigma_1 \sigma_3 = i \sigma_2 \text{ (cyclic perm.)} \quad (2)$$

$$\text{tr}(\sigma_i) = 0, \quad \det(\sigma_i) = -1 \quad (3)$$

$$(\vec{\sigma} \cdot \vec{a})(\vec{\sigma} \cdot \vec{b}) = (\vec{a} \cdot \vec{b}) + i \vec{\sigma} \cdot (\vec{a} \times \vec{b}) \quad (4)$$

Spinor representation of normalized vector \vec{P} :

$$\vec{P} = \psi^\dagger \vec{\sigma} \psi$$

$$\leftrightarrow \psi = \frac{1}{\sqrt{2(P_3 + 1)}} \begin{pmatrix} 1 + P_3 \\ P_1 + iP_2 \end{pmatrix} \quad (5)$$

Thomas-BMT equation in spinor or unitary representation:

$$\begin{aligned} \frac{d\vec{P}}{dt} &= \vec{\Omega} \times \vec{P} \\ \rightarrow \frac{d\psi}{dt} &= -\frac{i}{2} (\vec{\sigma} \cdot \vec{\Omega}) \psi \\ \text{or } \frac{d(\vec{\sigma} \cdot \vec{P})}{dt} &= -\frac{i}{2} [(\vec{\sigma} \cdot \vec{\Omega}), (\vec{\sigma} \cdot \vec{P})] \end{aligned} \quad (6)$$

Solution for constant $\vec{\Omega}$: (Axis \hat{n} , $|\vec{\Omega}| = \omega$):

$$\psi(t) = M(\hat{n}, \omega t) \psi(0), \quad \text{or} \quad (7)$$

$$(\vec{\sigma} \cdot \vec{P}(t)) = M(\hat{n}, \omega t) (\vec{\sigma} \cdot \vec{P}(0)) M^\dagger(\hat{n}, \omega t)$$

Rotation operation M by angle $\varphi = \omega t$ around axis \hat{n} :

$$\begin{aligned} M(\hat{n}, \varphi) &= \exp \left[-i (\vec{\sigma} \cdot \hat{n}) \frac{\varphi}{2} \right] \\ &= \cos \left(\frac{\varphi}{2} \right) - i (\vec{\sigma} \cdot \hat{n}) \sin \left(\frac{\varphi}{2} \right) \end{aligned} \quad (8)$$

Inverse operation:

$$\cos \left(\frac{\varphi}{2} \right) = \frac{1}{2} \text{tr}(M) \quad (9)$$

$$\hat{n} = \frac{i}{2 \sin(\frac{\varphi}{2})} \text{tr}(\vec{\sigma} M) \quad (10)$$

One-turn matrix $M_0(\theta)$:

$$M_0(\theta) = M_n \cdots M_2 M_1 \quad (11)$$

where θ is the starting (and ending) azimuth. The spin tune ν_{sp} and the spin closed orbit \hat{n}_0 (also called \hat{n}_0 axis or stable spin direction) are

$$\cos(\pi \nu_{sp}) = \frac{1}{2} \text{tr}(M_0(\theta)) \quad (12)$$

independent of θ

$$\hat{n}_0(\theta) = \frac{i/2}{\sin(\pi \nu_{sp})} \text{tr}(\vec{\sigma} M_0(\theta)) \quad (13)$$

2.7.3 Spin Rotators and Siberian Snakes

T. Roser, BNL

“Spin Rotators” rotate \vec{P} without changing \vec{v} .

Examples of Spin Rotators:

1. Wien Filter: Transverse E_x, B_z with condition $\frac{\vec{E} \times \vec{v}}{c^2} = \frac{1-\gamma^2}{\gamma^2} \vec{B}_\perp$,

$$\varphi = \frac{Ze(1+G)}{mc\beta\gamma^2} \int B_\perp ds$$

$$M_{\text{Wien}} = \cos \frac{\varphi}{2} - i\sigma_3 \sin \frac{\varphi}{2} \quad (1)$$

2. Solenoid:

$$\varphi = \frac{Ze(1+G)}{mc\beta\gamma} \int B_\parallel ds$$

$$M_{\text{Solenoid}} = \cos \frac{\varphi}{2} - i\sigma_2 \sin \frac{\varphi}{2} \quad (2)$$

Example: $\varphi = 90^\circ$ and $p = 1$ GeV/c requires $\int B_\parallel ds = 1.88$ T-m for protons and $\int B_\parallel ds = 5.23$ T-m for electrons.

3. Dipole:

$$\varphi = \frac{ZeG}{mc\beta} \int B_y ds$$

$$M_{\text{Dipole}} = \cos \frac{\varphi}{2} - i\sigma_3 \sin \frac{\varphi}{2} \quad (3)$$

Example: $\varphi = 90^\circ$ and $\beta \approx 1$ requires $\int B_y ds = 2.74$ T-m for protons and $\int B_y ds = 2.31$ T-m for electrons.

4. Full twist helical dipole with

$$\vec{B}(s) = B_0 \left(\sin \frac{2\pi s}{\lambda}, 0, \cos \frac{2\pi s}{\lambda} \right), \lambda > s > 0:$$

$$\varphi = 2\pi \left[\sqrt{1 + \chi^2} - 1 \right]$$

$$M = \cos \frac{\varphi}{2} - i(\sigma_2 + \chi \sigma_3) \sin \frac{\varphi}{2} \quad (4)$$

$$\chi \equiv \left(1 + \frac{1}{G\gamma} \right) \frac{ZeG B_0 \lambda}{mc \cdot 2\pi}$$

5. A "Full Siberian Snake" rotates \vec{P} by 180° ($\varphi = \pi$) around an axis in the horizontal plane with angle α from \hat{x} (Snake axis angle) [1]:

$$M_{\text{Snake}} = -i(\sigma_1 \cos \alpha + \sigma_2 \sin \alpha) \quad (5)$$

Note:

- (i) $M_{\text{Dipole}} M_{\text{Snake}} M_{\text{Dipole}} = M_{\text{Snake}}$.
(ii) Type 1 snake: snake axis is longitudinal ($\alpha = 90^\circ$)
(iii) Type 2 snake: snake axis is radial ($\alpha = 0^\circ$)

References

- [1] Ya.S. Derbenev, A.M. Kondratenko, PA 8 (1978) 115

2.7.4 Ring with Spin Rotators and Siberian Snakes

T. Roser, BNL

1. Ideal ring without spin rotators or Siberian snakes:

$$M_0(\theta) = \exp(-i\sigma_3 \pi G\gamma) \quad (1)$$

Note: $\nu_{\text{sp}} = G\gamma$.

2. Ring with solenoid (partial type 1 Siberian snake) at $\theta_0 = 0$ [1]:

$$\begin{aligned} M_0(\theta) = & \cos \frac{\varphi}{2} \cos(\pi G\gamma) \\ & - i\sigma_1 \sin \frac{\varphi}{2} \sin((\pi - \theta)G\gamma) \\ & - i\sigma_2 \sin \frac{\varphi}{2} \cos((\pi - \theta)G\gamma) \\ & - i\sigma_3 \cos \frac{\varphi}{2} \sin(\pi G\gamma) \end{aligned} \quad (2)$$

Note: $\cos(\pi\nu_{\text{sp}}) = \cos \frac{\varphi}{2} \cos(\pi G\gamma)$.

3. Ring with full Siberian snake with axis angle α at $\theta_0 = 0$:

$$\begin{aligned} M_0(\theta) = & -i[\sigma_1 \cos(\alpha - (\pi - \theta)G\gamma) \\ & + \sigma_2 \sin(\alpha - (\pi - \theta)G\gamma)] \end{aligned} \quad (3)$$

Note: $\nu_{\text{sp}} = \frac{1}{2}$ for all θ ; $\theta = \pi \rightarrow \hat{n}_0 = \hat{x} \cos \alpha + \hat{z} \sin \alpha$

4. Ring with two full Siberian snakes with axis angles α_a and α_b at θ_a and θ_b :

$$\begin{aligned} M_0(\theta) = & -\exp(-i\sigma_3 \chi) \\ \chi \equiv & \alpha_b - \alpha_a + (\pi - \theta_b + \theta_a)G\gamma \end{aligned} \quad (4)$$

Note: M_0 is energy independent for $\theta_b - \theta_a = \pi$; then $\nu_{\text{sp}} = \frac{1}{\pi}(\alpha_b - \alpha_a)$.

5. Ring with N pairs of full Siberian snakes with axis angles α_a^i and α_b^i at θ_a^i and θ_b^i :

$$\begin{aligned} M_0(\theta) = & (-)^N \exp(-i\sigma_3 \chi) \\ \chi \equiv & \sum_{i=1}^N (\alpha_b^i - \alpha_a^i) \\ & + \left[\pi - \sum_{i=1}^N (\theta_b^i - \theta_a^i) \right] G\gamma \end{aligned} \quad (5)$$

Note: M_0 is energy independent for $\sum_{i=1}^N (\theta_b^i - \theta_a^i) = \pi$; then $\nu_{\text{sp}} = \frac{1}{\pi} \sum_{i=1}^N (\alpha_b^i - \alpha_a^i)$.

References

- [1] T. Roser, Proc. Workshop on Siberian Snakes and Depolarizing Techniques (1989) p.1442

2.7.5 Depolarizing Resonances and Spin Flippers

T. Roser, BNL

Thomas-BMT equation with azimuthal coordinate θ as independent variable and the fields expressed in terms of the particle coordinates:

$$\begin{aligned} \frac{d\psi}{d\theta} = & -\frac{i}{2} \begin{bmatrix} G\gamma & -\xi \\ -\xi^* & -G\gamma \end{bmatrix} \psi \\ \xi = & -\rho y''(1 + G\gamma) \\ & -i \left[(1 + G\gamma) y' - \rho(1 + G) \left(\frac{y}{\rho} \right)' \right] \end{aligned} \quad (1)$$

where ρ is bending radius. Resonance strength is [1]

$$\epsilon_K = \frac{1}{2\pi} \oint \xi \exp(-iK\theta) d\theta \quad (2)$$

$K = kP \pm \nu_y$: intrinsic resonance from vertical betatron motion, P is the super periodicity
 $K = k$: imperfection resonance from vertical closed orbit distortions.

For isolated resonance: $\xi = \epsilon_K \exp(iK\theta)$. In frame rotating around \hat{y} with tune K ,

$$\begin{aligned} \psi_K = & \exp\left(\frac{i}{2}K\theta\sigma_3\right) \psi \\ \frac{d\psi_K}{d\theta} = & -\frac{i}{2} \begin{bmatrix} G\gamma - K & -\epsilon_K \\ -\epsilon_K^* & K - G\gamma \end{bmatrix} \psi_K \end{aligned} \quad (3)$$

Under adiabatic conditions:

$$P_y = \frac{(G\gamma - K)}{\sqrt{(G\gamma - K)^2 + |\epsilon_K|^2}} \quad (4)$$

Passage through an isolated resonance, Froissart-Stora Equation [2]:

$$\frac{P_{\text{final}}}{P_{\text{initial}}} = 2 \exp\left(-\frac{\pi |\epsilon_K|^2}{2\alpha}\right) - 1 \quad (5)$$

with $\alpha = \frac{d(G\gamma)}{d\theta}$ (crossing speed). Fast passage $\rightarrow P_{\text{final}} \approx P_{\text{initial}}$. Slow passage $\rightarrow P_{\text{final}} \approx -P_{\text{initial}} \rightarrow$ spin flip.

Artificial resonance from local oscillating field (ω = applied frequency, ω_0 = revolution frequency):

$$\begin{aligned} B_{\parallel} &= \hat{B}_{\parallel} \cos(\omega t) \\ \rightarrow \epsilon_K &= \frac{(1+a) \int \hat{B}_{\parallel} ds}{4\pi B\rho}; K = n + \frac{\omega}{\omega_0} \end{aligned} \quad (6)$$

$$\begin{aligned} B_{\perp} &= \hat{B}_{\perp} \cos(\omega t) \\ \rightarrow \epsilon_K &= \frac{(1+G\gamma) \int \hat{B}_{\perp} ds}{4\pi B\rho}; K = n + \frac{\omega}{\omega_0} \end{aligned} \quad (7)$$

Spin flip by ramping artificial resonance through resonance condition with speed α :

$$\alpha = \frac{K_{\text{end}} - K_{\text{start}}}{2\pi N} \quad (8)$$

where N is number of turns during ramp. For more than 99% spin flip:

$$K_{\text{end}} - K_{\text{start}} \geq 14\epsilon_K; \epsilon_K \geq \frac{1}{140N} \quad (9)$$

In a ring with Snakes ($\nu_{\text{sp}} = \frac{1}{2}$) additional higher order 'Snake' resonances [3] occur at energies close to intrinsic resonances of the ring without Snakes when the fractional vertical betatron tune

$$\Delta\nu_y = \frac{2k-1}{2(2l-1)} \quad (10)$$

With vertical closed orbit distortions Snake resonances also occur when

$$\Delta\nu_y = \frac{2k-1}{2(2l)} \quad (11)$$

References

- [1] E.D. Courant, R. Ruth, BNL-51270 (1980)
- [2] M. Froissart, R. Stora, NIM 7 (1960) 297
- [3] S.Y. Lee, S. Tepikian, PRL 56 (1986) 1635

2.7.6 Polarized Proton Beams and Siberian Snakes

A.D. Krisch, U. Michigan

In 1973, the first polarized proton beam was successfully accelerated in the Argonne ZGS. The

depolarizing resonances were not too strong in the weak focusing ZGS; thus it only required careful orbit control and fast betatron tune jumps to maintain the polarization while crossing the resonances [1].

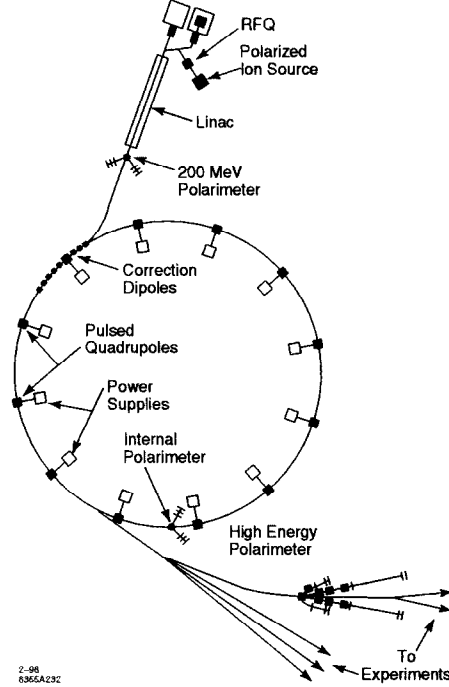


Figure 1: The complex individual depolarizing resonance correction hardware installed in the AGS [2].

In 1984, polarized protons were first accelerated at the Brookhaven AGS. Maintaining the polarization was much more difficult, because the strong-focusing AGS has strong depolarizing resonances. As shown in Fig.1, the AGS required complex hardware modifications for this difficult job. Moreover, 45 resonances needed to be corrected individually to maintain the polarization up to 22 GeV. A typical AGS resonance correction curve is shown in Fig.2 [2]. The polarized beam tune-up required 7 weeks of dedicated AGS operation. Clearly this individual resonance correction technique was impractical for a much higher energy, since the number of imperfection resonances to be crossed is $E / (0.52 \text{ GeV})$. Thus, it became clear [3] that Siberian snakes [4] (Sec.2.7.3-4) were needed to accelerate polarized protons above 30 GeV.

Many Siberian snake experiments have been performed at the 500-MeV IUCF Cooler Ring. The snake was a 2 T-m superconducting solenoid installed in a 6-m straight section, as shown in

Dr. T. Roser
AGS Dept
Brookhaven National Lab
Upton, NY 11973-5000

May 16, 1998

Dear Dr. Roser,

Enclosed you will find type set proofs of your article for the Handbook of Accelerator Physics and Engineering for your correction before final editing and publication. Even though time is very short, it is being sent to you by post so that you can see, with good resolution, how it will appear in the book.

While the type setting process is largely automated, some needed format changes and equations require human intervention, thereby creating opportunity for errors. For this reason it is extremely important for you to check every aspect PARTICULARLY EQUATIONS AND REFERENCES.

Please mark the corrections clearly and fax them back to me at 607 254 4552 as soon as possible. If you are unable to do it immediately, please note that it will be very difficult to include any corrections received after July 15 so if we have not heard from you by then we will assume that you have no corrections to submit.

Your expert and patient participation in this enterprise is very deeply appreciated indeed and we hope that you will have your copy of the finished book in hand early in 1999.

Very best regards,



Maury Tigner
cc A. Chao

(max for 90° scattering):

$$A_{\perp} = \frac{\sin^4 \theta'}{(3 + \cos^2 \theta')^2} \leq \frac{1}{9} \quad (21)$$

$$A_{\parallel} = \frac{(7 + \cos^2 \theta') \sin^2 \theta'}{(3 + \cos^2 \theta')^2} \leq \frac{7}{9} \quad (22)$$

The polarized electron targets in Møller polarimeters typically consist of thin ferromagnetic foils exposed to a ~ 100 gauss external magnetic field oriented with a given angle to the foil axis. A 8.3% maximum polarization of the target electrons (2 external out of 26 electrons per iron atom) has been achieved. The target polarization is measured to 1.5 – 2.0% precision (1.7% at SLAC).

The full beam polarization vector is determined by varying the foil orientation relative to the beam.

The analyzing power of Møller polarimeters need corrections due to orbital motion of inner shell target electrons [14] (momenta comparable to e^{\pm} rest mass).

Fig.3 shows the SLAC E-154 Møller Polarimeter [15, 16]

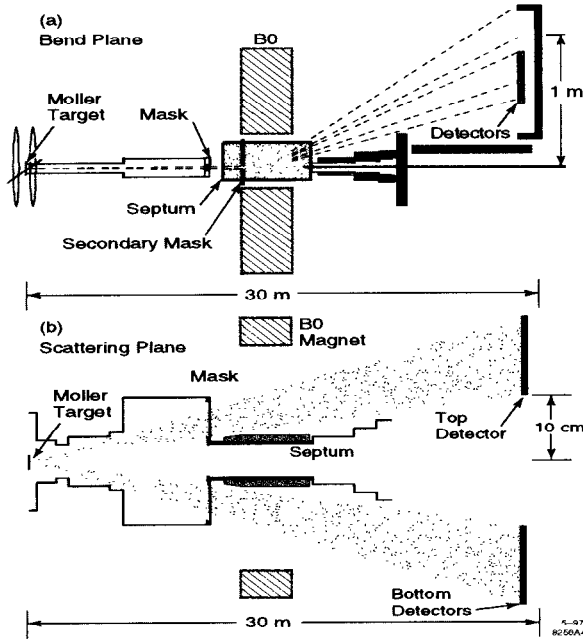


Figure 3: The SLAC Møller Polarimeter.

References

- [1] V.N. Baier and V.A. Khoze, Sov. J. Nucl. Phys. 9 (1969) 238

- [2] D.B. Gustavson et al, NIM 165 (1979) 177.
 [3] F.W. Lipps, H.A. Toelhoeck, Physica, XX (1954) 85 and 395
 [4] H.A. Toelhoeck, Rev. Mod. Phys. 28 (1956) 277
 [5] O. Klein, Y. Nishina, Z. Phys. 52 (1929) 853
 [6] U. Fano, J. Opt. Soc. Am., 39 (1949) 859
 [7] M. Woods, Proc. Workshop on High Energy Polarimeters, NIKHEF (1996)
 [8] A. Most, Proc. Workshop on High Energy Polarimeters, NIKHEF (1996); PhD Thesis (1996)
 [9] M. Placidi, R. Rossmanith, NIM A274 (1989) 79
 [10] B. Dehning, Dissertation der Facultät für Physik (1995)
 [11] L. Arnaudon et al, Z. Phys. C66 (1995) 45
 [12] K. Abe et al, PRL 78 (1997) 2075
 [13] C. Møller, Ann. Phys. (Leipzig) 14 (1932) 532; J. Arrington et al, NIM A311 (1992) 39
 [14] L.G. Levchuk, NIM A345 (1994) 496
 [15] H.R. Band, AIP Proc. 343 (1994) p.245
 [16] H.R. Band et al, SLAC-PUB-7370 (1997)

7.6.2 Proton Beam Polarimeters

T. Roser, BNL

Beam polarization is typically measured using a nuclear reaction in a plane that is perpendicular to the polarization direction. The polarization P and its statistical error ΔP (for $PA \ll 1$) are calculated as:

$$P = \frac{1}{A} \frac{N_L - N_R}{N_L + N_R}; \Delta P = \frac{1}{A} \frac{1}{\sqrt{N_L + N_R}} \quad (1)$$

A : Analyzing power of nuclear scattering or reaction

$N_L(N_R)$: Number of particles observed to the left (right) of the beam.

If the beam polarization is alternated between + (along the stable spin direction \mathbf{n}) and – (opposite to the stable spin direction \mathbf{n}) the polarization can be measured with much less sensitivity to systematic errors:

$$P = \frac{1}{A} \frac{\sqrt{N_L^+ N_R^-} - \sqrt{N_L^- N_R^+}}{\sqrt{N_L^+ N_R^-} + \sqrt{N_L^- N_R^+}}$$

$$\Delta P = \frac{1}{A} \frac{1}{\sqrt{N_L^+ + N_R^+ + N_L^- + N_R^-}} \quad (2)$$

See Tab. 1.

References

- [1] W. Haeberli et al, NIM 163 (1979) 403
 [2] H. Spinka et al, NIM 211 (1983) 239
 [3] S. Kato et al, NIM 169 (1980) 589
 [4] M. W. McNaughton et al, NIM A241 (1985) 435
 [5] D.L. Adams et al, Phys. Lett. B264 (1991) 462

Table 1: Typical nuclear reactions used for proton beam polarimeters.

Energy	Reaction	Kinematic region	Anal. power
< 0.1 GeV	$p + {}^{12}\text{C} \rightarrow p + {}^{12}\text{C}$	$\theta \approx 50^\circ$	$A \approx 0.8 \dots 0.9$
$0.1 \dots 1$ GeV	$p + {}^{12}\text{C} \rightarrow p + X$	$\theta \approx 15^\circ$	$A \approx 0.2 \dots 0.6$
$1 \dots 20$ GeV	$p + p \rightarrow p + p$	$t \approx -0.15 (\text{GeV}/c)^2$	$A \approx \frac{0.7 \text{ GeV}/c}{p_{\text{Lab}}}$
> 20 GeV	$p + p \rightarrow p + p$	$t \approx -0.0001 (\text{GeV}/c)^2$	$A \approx 0.04$
	$p + {}^{12}\text{C} \rightarrow \pi^{+(-)} + X$	$p_t \approx 0.5 \text{ GeV}/c; x_F \approx 0.5$	$A \approx 0.15$

7.7 CONTROLS AND TIMING

K. Rehlich, DESY

Change in computer hardware and software is rapid on the scale of accelerator construction schedules. Nevertheless software development must begin early to be ready in time. Most of the investment in a control system goes into the software and front-end electronics. For front end components the use of industrial standards is now quite safe as systems such as VME have shown a long lifetime.

Software development should be based on the new industrial methods. Object oriented tools have proven to be very powerful for control system design. In addition to object orientation, implementation on more than one platform leads to better design and helps to prepare for the inevitable evolution of computer systems during the project lifetime. Below we discuss the general architecture of a system and argue for a clear modular design of hardware and software together.

Architecture As shown in Fig.1, the overall architecture consists of three layers of computers. A top level with display or client programs, a front-end layer with device servers and I/O and a middle layer with powerful group servers. The upper layer is the interface to the operators. These upper services should be available to the consoles in the control room, the experts working at the machine and the specialists in their offices. All of them should be able to use the same programs. Only the level of details presented should be different, but nonetheless available to all levels of users. Modifications of device data must be protected with access rights.

Since a lot of users and client programs access a lot of data from the front-end and the middle layer, a fast network is necessary to decouple the display stations. A net switch that routes packets from the clients to their servers provides the important bandwidth.

Client programs often need information from a group of devices or need to operate on such a group. A middle layer server should provide such collective reports and controls. Likewise, the middle layer should supply frequently requested data of all its front-end computers in a single block transfer. Proxy services may also be added since the middle layer servers can be faster than the front-end computers. But, a direct access to front-ends (and not just for debugging purposes) is still necessary. In general, the middle layer implements higher services and improves the performance of the system.

Data bases, file servers, simulation servers and other kind of servers without direct device connections should be placed in the middle layer also. Subsystems of the machine use their own subnet with front-end computers. The front-ends are distributed and close to the devices of the machine. Some hardware is directly connected to the device servers, other equipment use field busses to connect the front-end electronics to the device servers. Fieldbus electronics introduce a further level of computers in the system. Programmable Logic Controller (PLC) and "intelligent" devices are examples of such stand-alone processors.

All group servers and most front-end servers are equipped with disk drives. The other device servers mount their file systems from the corresponding group server. If a front-end has to run stand-alone in case of a network problem, it should have a direct connected disk or must have the program and data files in memory. Archiving of all data from the equipment can consume a high portion of the network bandwidth if the storage is not in a local disk.

Front-end computer Most of the device input and output channels connect via VME modules or fieldbus electronics to the device servers. The VME system is designed for a reliable industrial electronic environment. Almost any computer, analog or digital input/output module and field-